PURGE SYSTEM FOR OPTICAL METROLOGY TOOL

INVENTOR: Jeffrey E. McAninch

PRIORITY CLAIM:

The present application claims priority to U.S. Provisional Patent Applications Serial No. 60/283,115, April 11, 2001, and Serial No. 60/336,854, filed November 1, 2001, both of which are incorporated herein by reference

TECHNICAL FIELD

The subject invention relates to optical metrology devices which require a controlled ambient atmosphere to improve measurement. More specifically, the invention relates to an optical metrology instrument that includes a gas-flow system for the purpose of purging the optical path to stabilize measurement and clear the path of optically absorbing species.

BACKGROUND OF THE INVENTION

The semiconductor industry is presently developing photolithographic methods utilizing 157 nm wavelength laser light as the next step in the continuing reduction of device length scales. Metrology tools are presently needed to support this development, for instance by providing measurements of the optical properties of candidate materials over the spectral range from ~140 to ~200 nm. These wavelengths lie within a region known as the vacuum ultraviolet (VUV), in which the high absorption coefficients of oxygen and water vapor lower the attenuation length in standard air to fractions of a millimeter. (Historically, this light could only be observed under vacuum conditions, hence the designation.) Achieving the transmission and stability necessary for a VUV optical metrology tool, in which the optical paths are 0.5-2 m, therefore requires oxygen and water concentrations in the low parts-per-million (ppm) range averaged over the entire optical path. In the near future, as production facilities incorporating 157 nm lithography come online, larger numbers of these tools — capable of handling production line throughput — will be required. A major engineering challenge in the development

of 157 nm metrology is simultaneously providing high wafer throughput and low optical absorption.

In the prior art, Freeouf, in US Patent 6,222,199 B1, incorporated herein by reference, teaches the benefits of performing specular bi-directional ellipsometric measurements in a geometry where the entire light path is maintained in a controlled ambient to prevent absorption and local excitation. At present, multiple commercial manufacturers offer VUV spectroscopic ellipsometer (SE) products that maintain a controlled ambient via housing the entire metrology apparatus inside a sealed container filled (purged) with purified nitrogen gas.

A design that places the complete instrument in a sealed container has two notable disadvantages. First, the purged volume is significantly larger than the volume that encloses the VUV optical path alone and must house multiple components – e.g., optical elements, optical mounts, electrical components, electrical wiring, actuators, adhesives, etc. - which do not need to be in the purged atmosphere. This places stringent and overly restrictive requirements on component materials since component and material out-gassing can degrade the purge environment. Furthermore, a high volume purge-gas flow is required to cool the system electronics. Second, the system requires some sort of sealable entry port or load-lock to enable sample (wafer) insertion while preventing the introduction of oxygen and water vapor contaminants into the chamber. This necessarily hinders wafer handling and substantially reduces throughput and usability.

Accordingly it would be desirable to provide a VUV metrology tool architecture wherein the purged volume is minimized - approaching the volume of the VUV optical path - and the instrument does not require a load-lock to isolate either the sample (wafer) or the metrology tool from the laboratory environment.

SUMMARY OF THE INVENTION

The subject invention relates to a VUV optical metrology system that incorporates a gas-purge of the optical path – the light path that connects the illuminator, the sample and the detector. The metrology system avoids the use of a continuous, solid, barrier to separate the optical path from the laboratory environment; therefore, no load-lock is required. A substantially oxygen and water-vapor free environment is created and

maintained by hydrodynamic flow of purified inert purge-gas that is introduced at least one injection point along the optical path.

The flow acts to displace optically adsorbing contaminants from the optical path, remove optically absorbing species from the surfaces bounding the optical path and, inhibit back diffusion of the chemical contaminants displaced in the flow. The purge-gas flow simultaneously prevents back- diffusion of atmospheric constituents from the laboratory environment to the optical path. This is achieved using a geometrical arrangement where the system optics is maintained in a housing that has a substantially planar surface.

The measurement process is initiated by raising the wafer from a load position to a measurement position where the wafer surface is substantially parallel to the housing surface where light is incident on the wafer at a measurement location. In the measurement position the volume bounded by the wafer and the housing approximates a thin disk. The flow system is arranged such that purge-gas is injected into the bounded volume at flow sufficient to purge the bounded volume in the vicinity of the measurement location. The purge gas flows outward from the measurement location and is exhausted at the wafer boundary.

The subject purge system will also improve measurements at longer wavelengths. More specifically, the purge system will help to stabilize temperature and make measurements conditions more uniform. This will lead to more accurate and repeatable measurements.

BRIEF DESCRIPTION OF THE DRAWINGS

Figure 1 illustrates a preferred embodiment for purging of the optical path.

Figures 2a-2b schematically illustrate the layout of an optical metrology tool where the optics housing isolated from the sample space (2a), and the purge-gas flow (2b) in the measured region.

Figure 3 illustrates an embodiment of a gas-purged optical metrology instrument.

Figures 4 is a plan projection illustrating the flow of the purge gas through the instrument.

Figure 5 is a perspective view, partially in section of the gas-purged metrology instrument of the subject invention.

Figure 6 is an enlarged, cross-sectional view of the gas-purged metrology instrument of the subject invention.

Figures 7a-7c illustrate the results of a finite-element computer model for the time evolution of the gas composition in the vicinity of the measurement region following sample exchange.

Figure 8a-8c illustrate the results of a finite-element computer model for the time evolution of the gas temperature in the vicinity of the measurement region following sample exchange.

Figure 9 shows the wavelength dependent detector output illustrating the influence of the gas purge on detector signal in the VUV, DUV and NUV spectral regions.

Figure 10 illustrates the time evolution of the detector output following interruption of the purge-gas stream.

Figure 11 illustrates the measured temporal stability and reproducibility of the VUV and NUV signals following repetitive wafer load/unload cycles.

DETAILED DESCRITPION OF THE PREFERRED EMBODIMENTS

Figure 1 depicts a cross sectional view of an optical metrology system 20 that implements a preferred embodiment of the inventive gas-purge scheme. The figure depicts a portion of the optics housing 22 that contains two cylindrical beam transport tubes that serve to transmit the incident 26 and reflected 28 radiation. Wafer 24 is illustrated at the measurement position where incident illumination 26 interacts with wafer 24 at measurement location 30. Reflected radiation 28 is transmitted to a detection system that is not shown in the figure. As illustrated in the figure the lower surface of optics housing 22 is substantially planar so that the volume 32 bounded by the lower surface of housing 22 and wafer 24 approximates a thin plate.

A flow of high purity purge gas 34 is injected upstream and flows through a beam tube toward measurement location 30. The flow is exhausted at the periphery of wafer 24. For VUV applications the purge gas must be substantially transparent in the spectral region between 140 and 175 nm. Suitable gases would include nitrogen, helium and argon. For high purity applications preferred sources include the boil-off from cryogenic liquids and cylinders of ultra-pure compressed gas. The purge gas is injected into the system at or somewhat above atmospheric pressure.

Figures 2a-2b schematically illustrate the layout of an optical metrology tool 40 where lenses 36 isolate the interior of optics housing 22 from bounded volume 32. Figure (2a) illustrates a schematic layout of the system and further includes wafer transport assembly or stage 38 which serves both to move wafer 24 between wafer-load and wafer-measurement positions, and to sequentially locate multiple locations of the wafer surface at measurement location 30, so that a plurality of sites on the wafer surface may be measured. Here the interior of optics housing 22 is isolated from the sample and the laboratory environment by lenses 36. The isolation could be accomplished by installation of a variety of optical components including lenses, windows, polarizing elements, transmissive elements, diffractive elements and optical systems containing reflective components. Furthermore the optical systems must efficiently transmit VUV radiation and therefore be fabricated from VUV transmissive material such as fused silica, fluorine-doped fused silica, quartz, CaF_2, SrF_2, BaF_2, MgF_2, LaF_3 and LiF. Consequently, only the volume bounded by the exterior surfaces of lenses 36, optics housing 22 and wafer 24 requires dynamic gas-purging. Figure 2b is a magnified view of the region surrounding measurement position 30. In this case the injection point is located between the beam tubes and the purge gas flow 34 is exhausted at the periphery wafer 24.

Figures 3 to 6 illustrate a preferred embodiment of a gas-purged spectroscopic ellipsometer. The system incorporates optics plate 62, optics housing 22, illuminator 64, sealed housings 65, 66, beam-transport tubes 67, 68, spectrometer/detector assembly 70 and processor 72. In the commercial embodiment, a rotating compensator is located in housing 73. Wafer transport assembly 38 and wafer 24 are below optics plate 62 and are not visible in the figure. Beam-transport tubes 67, 68 and housings 65, 66 are utilized to

separate the optical path from the laboratory environment. In the preferred embodiment housings 65, 66, illuminator assembly 64 and spectrometer/detector assembly 70 include ports for vacuum pumping and gas purging the enclosures. Where needed, electrical feed-throughs are included. In the preferred embodiment beam transport tubes 67, 68 housings 65, 66, illuminator assembly 64, spectrometer/detector assembly 70 and optics housing 22 are purged by a flow of high purity N_2.

Illuminator 64 can include one or more light sources. In one preferred embodiment, a 50W VUV-grade D_2 discharge-lamp is utilized for measurement wavelengths between 140 and 400 nm, and a W lamp is used for wavelengths between 400 and 850 nm. Alternative embodiments may incorporate a single, broad band source or narrow band sources including lasers, lamps and amplified stimulated emission sources. Light from the illuminator is transmitted through beam-transport tube 67 to housing 65 where it is turned by mirror towards the sample. The incident illumination is polarized and focused (by a lens and polarizer, not shown) onto the wafer surface where it reflects from and interacts with the surface of sample 24.

The reflected radiation is turned by mirror 80 and is collected and transmitted through beam-transport tube 68 to housing 66 and spectrometer/detector assembly 70 to analyze the polarization state change in the incident illumination produced by reflection from and interaction with sample 24. Processor 72 serves to automate the measurements and analyze the output signals generated by spectrometer/detector assembly 70.

The design elements for gas-purging the optical paths illustrated in Figs.3 to 6 can be implemented in a broad variety of optical metrology tools including spectroscopic ellipsometers, spectroscopic reflectometers, spectroscopic polarized beam reflectometers, scatterometers and optical CD measurement tools. Furthermore, multiple instruments can be combined on a common platform to comprise a single broad-band optical metrology instrument that incorporates multiple spectroscopic metrology capabilities, e.g. reflectometry, scatterometry and reflectometry. Here it is particularly advantageous to provide a processor to analyze the output signals generated by the various detectors. In the preferred embodiment the analysis protocols can treat the output signals individually or in combination to evaluate the characteristics of a sample. The detector outputs may include signals corresponding to changes in magnitude, changes in polarization state,

changes in magnitude of polarized radiation and scatter, that result from the interaction with and reflection of illumination reflected from the sample, measured at a plurality of wavelengths.

Prior to initiating a detailed mechanical design for the proof-of-principle SE tool, a finite element model analysis simulator was employed to model the dynamic purge system performance and simulate the purging process in a prototype tool design. A fully 3D model was developed using the commercially available finite-element package FloWorks. FloWorks functions as an add-in to SolidWorks, a standard mechanical design package, so that mechanical drawings of the prototype design could be computer generated. The intent of the model was to permit a parametric study of flow system performance as a function of the design variables assessing the temporal evolution and temporal stability of chemical purity, flow geometry, and gas temperature as a function of boundary shape and flow rate. The stability against perturbations, time required for the initial purge, time scales for recovery from wafer exchange, and the variation in system performance as a function of wafer position (wafer edge exclusion) were determined.

The embodiment shown in Figures 3 to 6 was used in the simulation. Figures 7a-7c and 8a-8c illustrate the time evolution (a: 1sec, b: 5 sec, c: 10 sec) of the O_2 concentration and gas temperature as a function of position across a 2-d slice of the bounded volume within the measurement region following a wafer load that occurs at time, t = 0.

The initial conditions used in the simulation assumed a 300 mm diameter wafer located 1 mm below the bottom of the optics plate with the measurement location 3 mm from the wafer edge. The initial chemical composition within the bounded volume was a mixture of 80% N_2 and 20% O_2 (room air) at a pressure of 1 atm and a temperature of 28C. Solids surfaces were maintained at a fixed temperature of 30C. A continuous flow of N_2 purge gas is injected into the bounded volume at t = 0, at flow rate of 500 standard cubic centimeters per minute (sccm), at 28C, at 3 injection points: one along each of the spectroscopic ellipsometer light paths 26 and 28, the outer purge, and one through a fitting placed near the auto-focus system 82, the central purge. In the simulations, a back-flow of room air at 1000 sccm is injected at the wafer boundary to account for back-

diffusion of room-air toward the measurement region. The total flow is exhausted at the wafer boundary into a reservoir of room air at 1 atm and 20C.

Figures 7a-7c illustrate the results of a finite-element computer model for the time evolution of the gas composition in the vicinity of the measurement region of the prototype system following sample exchange. The model utilized the initial conditions and parameters described in the preceding paragraph. Figure 7a-7c show the gradient in O_2 concentration, in a 2-d plane passing through the measurement location, 1, 5 and 10 sec after sample exchange. The O_2 concentration is reduced to below 20 ppm within 10 sec. Consequently, the bounded volume is essentially free of optically absorbing species 10 sec following wafer exchange. The model simulations predict that high-throughput VUV optical metrology can be performed in a system without the requirement for a solid physical barrier between the measured region and the laboratory environment.

In high performance optical metrology it is essential to minimize thermal excursions in the optical system, particularly those induced in the vicinity of the wafer following wafer exchange. Thermal variations in the ambient surrounding the measurement region can produce spatial inhomogeneity of the refractive index of the ambient that comprises the optical path, confusing the measurement and complicating the analysis. Figures 8a-8c illustrate the evolution of the gas temperature within the measurement region of the prototype system following sample exchange. The model utilized the initial conditions and parameters described above. Figure 8a-8c show the gradient in temperature, in a 2-d plane passing through the measurement location, 1, 5 and 10 sec after sample exchange. The gas is thermally equilibrated within 5 sec throughout the key measurement region. Consequently, the simulations predict that the limitations on wafer throughput imposed by the purge approach are chemical rather than thermal.

A number of additional simulations were undertaken to establish the parametric variation of the system performance on the design variables. The simulations were computationally intensive, e.g. the generation of time-dependent results illustrate in Figs. 7 and 8 required ~ 48-72 hrs of processing time on a 1 GHz Pentium III with 1 GB of RAM. The output files required ~ 6 GB of disk space. In aggregate the simulations reveal:

a) Simpler designs for the purge orifice and surrounding area work better. Attempts to be clever by shaping surfaces always seemed to increase the flushing times and required larger flows to get the same exclusion of room air. The final design essentially brought the metal as close as was reasonable to the optical path.

b) Flow velocities of 20-30 cm/s were sufficient in the model to block intrusion of room air into the measurement area at the level required for VUV-SE. These velocities are well within the laminar flow regime for the spatial scales involved.

c) For a 1 mm gap between the wafer and optics plate, 20-30 cm/s flow velocities can be obtained in the vicinity the purge orifice when flow rate is ~ 1000 sccm.

d) Flushing times to reach <20 ppm O_2 over the entire optical path were ~10 s when the central volume was filled with room air.

e) At the required flow, pressure gradients in the system are small.

f) At the required flow, the purge gas thermally equilibrates rapidly.

g) Flow rates of ~ 1000 sccm through the purge orifice are sufficient to maintain low ppm O_2 levels even with the wafer removed.

A VUV spectroscopic ellipsometer (VUV-SE) was designed and implemented utilizing the above described simulation results. The VUV-SE instrument was based on the assignee's Opti-Probe OP5300 frame and optics plate. This choice simplified the design and construction. A pre-existing OP7300 optics plate was adapted to the VUV requirements, and placed into a pre-existing OP5300 frame. The VUV-SE optical path, enclosed and purged, was designed to fit within this platform. The design minimized the purged volume and was capable of supporting a vacuum of $< 1\times10^{-6}$ atm to facilitate pump-purge "clean-up" of the enclosed space following exposure of the system to the atmosphere. Consequently, all of the VUV optical components, the VUV light source, VUV spectrometer, turning mirrors, Rochon polarizer and analyzer, and waveplate stepper motor are placed in O-ring sealed housings. Lids are removable for access, and have ports for pumping, purge inlet and outlet, and electrical feedthroughs. Beam tubes (16 mm or 25 mm clear apertures) are used to enclose the optical path between housings.

An Alcatel Drytel pump is used for evacuating the system. This oil-free molecular drag pump with diaphragm backing pump is designed for clean room use, and can be exhausted into the room. A mechanical vacuum gauge is used for monitoring rough pump-down and let-up, and an Alcatel Cold Cathode/Pirani gauge is used for measuring lower pressures. Commercial O-ring fittings (Kwik-Flange, Swagelok, and Quick-Disconnect) are used for tube-tube and tube-housing attachments, and to assemble the external gas handling system. A plate with a captured O-ring was fabricated to cover the purge orifice from below (with the stage in the load position), allowing the entire system to be pumped out.

The primary N_2 supply is house nitrogen gas (boil-off from liquid nitrogen) although bottled gas can be used. To prevent residual contamination (chronic or acute) in this supply from reaching the purge system, the N_2 is passed through a custom two-stage purifier purchased from Innovative Technologies. The first stage of the purifier is an activated carbon molecular sieve that removes trace volatile organics. The second stage is a reduced copper powder column to remove water and oxygen. Both stages can be regenerated in house. The N_2 flow to the VUV tool is controlled using a multi-port manifold with fine flow adjust, flow meters and 0.5 μm point-of-use filters. Gas is transported from the manifold to the tool using 1/8" Teflon tubing connected with stainless steel Swagelok fittings.

Figures 9, 10 and 11 show the results of a series of experiments performed on the VUV-SE system. In these experiments, UV spectra were recorded with the wafer located at several different wafer positions as a function of purge-gas flow rate. System performance (efficiency of purging) was evaluated by comparing the time evolution of the detected VUV light intensity to the detected near UV (NUV) intensity as function of flow rate. As describe below and illustrated in Figure 9 the purge flow has a marked influence on VUV transmission but a negligible effect in the NUV spectral range. Consequently, the ratio of the normalized VUV/NUV intensity is a good quantitative measure of the effect of the purge on optical transmission.

Referring to Figure 9, the measured detector signal (CCD Voltage) is plotted vs. wavelength over a wavelength region between 100 and 325 nm. Spectra were taken with a 1024 windowless CCD array detector with 16 averages per read with the purge on (red)

and off (blue). In the spectral range spanning ~ 200 – 250 nm, which we refer to as the NUV, the purge has no observable effect on the detector signal. However, in the spectral range spanning ~ 150 – 175 nm, which we refer to as the VUV, the purge has a marked influence. In the absence of the purge, the light is fully attenuated by atmospheric absorption and the CCD voltage, corrected for background noise, is 0. With the purge on the CCD generates a large signal (3Volts peak).

Figure 10 illustrates the effect of perturbing the purge gas flow on the optical transmission. The normalized intensity ratio (VUV/NUV) is plotted as a function of time for various operating conditions. The wafer was placed with the measurement location coincident with the wafer center, the purge gas flow was initiated and system was optically focused. Spectra were recorded approximately every 30 s. At t = 8 minutes the central purge was stopped. This had a negligible effect on the VUV transmission. At t = 10 minutes the outer purge flow was terminated. This had an immediate effect on VUV transmission and the VUV signal dropped to 0 at t = 13.5 minutes. At this time both central and outer purge flows were resumed. The VUV transmission took 5-7 min to recover to ~ 98% of it's initial value. At t=20 minutes we attempted to inject a transient pulse of air into the bounded volume near the wafer edge. The transient pulse was generated with an air gun driven compressed N_2 operated in room air - the gun creates a Venturi action so that the bulk of the nozzle output is room air. It proved difficult to produce an observable effect. At 23 min the gun was moved to ~1 ft from the edge of the wafer-chuck, and angled upward to deflect the air off the lower surface of the optics housing and into the bounded volume between the optics housing and the wafer surface. The gun was operated for ~30 s until the next spectrum was recorded. The air-gun affected signals throughout the VUV, DUV and NUV; however, the detection system fully recovered within 30s of turning-off the air-gun.

Figure 11 illustrates the measured temporal stability and reproducibility of the VUV and NUV signals following repetitive wafer load/unload cycles. Repeat measurement cycles were made at the wafer center. A measurement cycle encompassed the following steps

a) maintain the wafer at load the load position for 30 s.

b) move the wafer to the measurement position with the measurement location at the wafer center

c) focus the optical system

d) record a number, n, of consecutive spectra

e) return the wafer to the load position

In order to address any systematic variation in sensitivity of the spectral response to focus repeatability, the measurements were split into 2 sub-experiments, B1 and B2. In B1, the focus was re-established prior to recording each spectrum. In B2, the focus was established initially, and frozen while the subsequent spectra were recorded. For experiment B1, n = 25, for B2 n = 27. As illustrated in Fig. 11, the time evolution of the normalized VUV/NUV intensity ratio is both independent of time and, within the experimental inaccuracies, independent of focusing protocol.

In the preferred embodiment, the wafer transport system 38 (Figure 2) includes a vacuum chuck for holding the wafer in place. The chuck is, in turn, mounted upon two or more movable stages for positioning the wafer with respect to the measurement spot. Common stage combinations include full X and full Y stages, 1/2 X and 1/2Y plus rotary (theta) stages and polar coordinate stages (R, theta). In the preferred embodiment, the stage arrangement will include the ability move the chuck in the vertical or Z axis. In the wafer load position, the chuck is lowered an amount sufficient so the wafer can be easily loaded on top of the chuck. Once the wafer is loaded, the stage will raise the chuck to bring the wafer into close proximity to the bottom surface of the optics plate. Preferably, the separation between the wafer and the optics plate will be between 10 microns and 2 millimeters.

In the preferred method of the subject invention, the purge flow is initiated prior to or during the time the chuck is being raised into the measurement position. Raising the chuck into the measurement position while the purge gas is flowing helps to drive absorbing species out of the measurement area. More specifically, as the chuck is raised and the wafer comes into close proximity to the bottom surface of the optics plate, the gas in the region will be squeezed outwardly and replaced by the purge gas. In this manner, the region around the measurement spot will be rapidly cleared of the absorbing species,

allowing a measurement to be taken relatively quickly after the wafer is in the measurement position.

The present invention has utility beyond operation in the VUV measurement wavelength range. More specifically, the initial experiments demonstrate that the subject approach functions to provide a stable, homogenous environment for measurement. More specifically, the environment around the measurement area is composed of a known, homogenous purge gas at a controlled and stable temperature. This condition leads to far greater precision and repeatability of the measurement. Accordingly, the use of the subject invention may be warranted for measurement in any wavelength region where greater precision and repeatability is desired.

As seen in the figures, in the preferred embodiment, the primary purge gas flow is directed down towards the wafer near the measurement area. The flow incoming is directed radially inwardly and down to the wafer. When the flow strikes the wafer, it is turned and passes over the wafer in a radially outward direction.

It is within the scope of the broader aspects of the subject invention to provide any flow path for the purge gas which causes the gas to pass over the measurement area. For example, the purge gas can be initiated on one side of the wafer and passed across the wafer in a curtain-like fashion. The flow path should be arranged so that it passes the measurement area.

While the subject invention has been described with reference to a preferred embodiment, various changes and modifications could be made therein, by one skilled in the art, without varying from the scope and spirit of the subject invention as defined by the appended claims.